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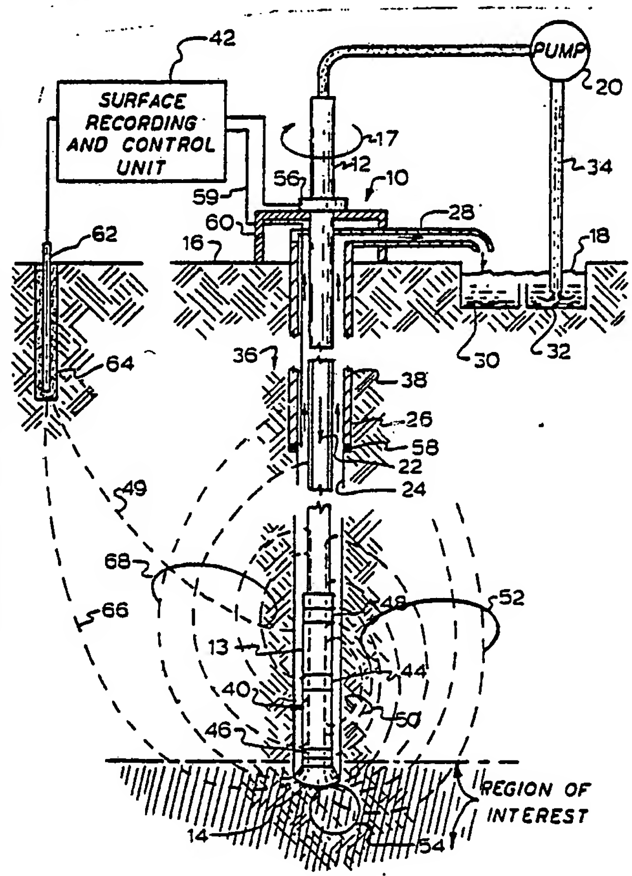
(54) Title: APPARATUS AND METHOD FOR LOGGING WELLS WHILE DRILLING

(57) Abstract

An information while drilling apparatus and method for characterizing strata in the vicinity of a drill bit at the lower end of a drill string, including a down-hole module unit (40) and surface receiving and control (42) units. Excitation currents are caused to pass through the drill string (12) drill bit (14) and surrounding strata (36) and the current flowing through the drill bit is sensed by a first toroidal transformer (46) that encircles the drill string immediately above the drill bit (14). The sensed current, which is characteristic of the strata (36) adjacent to and below the drill bit, is detected to form logging signals. A second toroidal transformer (46) couples the logging signals to the electrically conductive drill string (12) for transmission to the surface receiving unit (42). The frequency of the excitation current is adjustable to permit characterization of the strata at various distances from the drill bit. The frequency of the transmitting signal is also adjustable to compensate for varying degrees of signal attenuation along the transmission path. Control of the excitation and transmission frequencies is effected by communications from the surface control unit (42) in response to stored operating instructions or operator inputs.



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"Apparatus and Method For Logging Wells While Drilling"

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates generally to subterranean instrumentation and telemetry systems and relates more specifically to apparatus for logging wells by remote sensing and real-time surface recording of well drilling parameters.

Description of the Prior Art

During the drilling of a well, certain parameters concerning the drilling operation and the earth strata being drilled through are of interest. Knowledge of the materials comprising the earth strata is valuable to the drilling rig operators. This knowledge enables the weight, speed, and torque of the drill bit to be adjusted to obtain optimum drilling performance. Knowledge of the strata also permits a suitable selection of a drilling fluid, which is pumped down the hollow drill pipe to convey the drill tailings to the surface, and to keep the hydrostatic pressures in balance.

It is desireable to identify the strata beneath the drill bit, prior to its contamination by the drilling fluid, as well as the strata that has been drilled through. Information concerning the drill bit, such as torque and weight on bit, is of interest and can be utilized to optimize drilling performance.

Knowledge of certain drilling fluid characteristics, such as temperature and pressure, is useful as well.

All of this information is most useful and most indicative of the drilling environment when it is obtained while in the process of drilling. Parameters concerning the drilling operation should be measured in the dynamic drilling environment and relayed in real-time to the surface to permit the drilling rig operators to optimize drilling performance. Identification of the earth strata while drilling is also desireable. One common method of strata identification requires the drilling to be halted and the drill pipe and drill bit to be completely removed from the bore hold to allow a wire-line sensor to be lowered into the well for strata identification. By this time, the strata has been contaminated by the drilling fluid which alters its resistivity and makes it more difficult to identify and evaluate. Then, when the measurements are completed, the sensor is removed from the bore hole and the drill pipe and drill bit are replaced. This very time consuming and expensive procedure would be unnecessary if the strata could be identified while drilling.

Several problems are encountered in logging wells, in both the measurement of the parameters of interest and in the communication of these measurements to the top of the well. The down-hole environment itself is quite harsh with elevated temperatures and pressures. Drill bit vibrations may be quite high. The drilling fluid flowing through the drill pipe bit may be highly abrasive. One design consideration is that the down-hole measurement unit must be durable enough to withstand this hostile environment for long periods of time. Another design consideration

is that electric power must be provided to the down-hole measurement unit for powering the measurement sensors and circuits. Additionally, data gathered by the down-hole measurement unit must be communicated, in some manner, to the surface to provide real-time information while drilling (IWD). Ths use of cables to provide electric power to the down-hole measurement unit and to provide data communication between the down-hole measurement unit and a surface recording unit are impractical with standard rotary drilling procedures. Electromagnetic signals, propagated through the earth, may be used to communicate between the down-hole measurement unit and the surface recording unit, but signal attenuation and noise problems limit the usefulness of this approach.

A substantial amount of prior art exists concerning well logging apparatus. However, only the most appropriate art will be cited herein. Toroidal transformers, which are toroidal cores of magnetic material wound with wire, are known for use in well logging apparatus. Still discloses in U.S. Patent Nos. 3,793,632 and 4,302,757 methods of using toroids to transmit data along a drill string. Silverman, in U.S. Patent No. 2,354,887, discloses the use of a toroidal transformer for sensing a surface generated current in a drill pipe that is proportional to the conductivity of the earth strata between the drill bit and the surface. Arps in U.S. Patent No. 3,305,771 and Martin in U.S. Patent No. 3,079,549, disclose the use of toroidal transformers to sense current flow in drill pipes for logging wells. See also "Theory of Transmission of Electromagnetic Waves Along a Drill Rod in Conducting Rock" by James R. Wait and David A. Hill; Trans. on Geoscience Electronics, pp. 21-24,

Vol. GE-17, No. 2, April, 1979.

The use of toroidal transformers for inducing a modulated alternating current indicative of logging data in a drill pipe at a subsurface location for transmission to the surface is disclosed by Silverman in U.S. Patent No. 2,354,887 and 2,411,696, by Scherbatskoy in U.S. Patent No. 4,057,781, and by Zuvela in U.S. Patent No. 4,181,014. Scherbatskoy, in U.S. Patent No. 4,057,781, also discloses a toroidal transformer employed as a device for sensing modulated alternating current in a drill pipe at the surface of a well as part of a circuit for receiving transmitted logging data. Silverman, in U.S. Patent No. 2,411,696, discloses a similarly functioning toroidal transformer that is located below the surface for reduced noise sensitivity. However, none of the above cited patents disclose the use of a toroidal transformer located in close proximity to a drill bit for inducing a current through the drill bit in order to measure the conductivity of the surrounding earth strata.

A down-hole electrical generator powered by fluid flow is of interest in the present invention. One such generator is disclosed by Godbey in U.S. Patent No. 3,305,825.

Alternative electrical and electromagnetic means for transmitting logging data from an area near a drill bit to the surface of a well are known in the art of well logging. See, for example, U.S. Patent Nos. 2,181,601 (Jakosky), 3,967,201 (Rorden), and 4,087,781 (Grossi) for various alternatives.

SUMMARY OF THE PRESENT INVENTION

A primary object of this invention is to

provide improved well logging apparatus for real-time logging of well drilling information.

Another object of this invention is to provide well logging apparatus capable of providing information indicative of underlying strata, that is to say strata situated beneath a drill bit, at a time prior to intrusion by drilling fluid.

An additional object of this invention is to provide well logging apparatus that, during the drilling operation, is capable of imparting alternating electrical currents of a range of frequencies into the surrounding strata and measuring parameters relating to the conductivity and dielectric constant of the strata at various distances from the drill bit.

A further object of this invention is to provide improved well logging aparatus that, during the drilling operation, is capable of two way communication along the drill pipe between a down-hole measurement unit and a surface recording and control unit.

Still another object of this invention is to provide well logging apparatus having variable frequency communication means between a down-hole measurement unit and a surface recording and control unit for the optimization of data transfer therebetween.

Still another object of this invention is to provide well logging apparatus with a communication link that is capable of selective transmission of real-time logging data between a down-hole measurement unit and a surface recording and control unit with the selection based on the value of the data and the available bandwidth of the communication link.

A still further object of this invention is to

provide well logging apparatus with passive current couplers and conductors for the reduction of signal attenuation of logging data and control signals during transmission along a conductive drill pipe.

Another object of this invention is to provide well logging apparatus with active signal repeaters dispersed along the drill pipe to reduce the attenuation of signals transmitted therethrough.

These and other objects, which will hereinafter become apparent, are accomplished in accordance with the illustrated embodiments of this invention by providing an information while drilling (IWD) apparatus comprising a down-hole measurement unit and a surface recording and control unit. The down-hole measurement unit is contained in a drill collar at the end of a drill pipe just above the drill bit and includes the following: a data acquisition subsystem, and a power subsystem.

Included in the data acquisition subsystem are two toroidal transformers, coaxial to the drill collar and in the surrounding strata. The second toroidal transformer is located just above the drill bit and senses the portion of this induced current that passes through the drill collar and enters the strata through the drill bit. Data concerning the conductivity and dielectric constant of the surrounding strata can be computed from the phase shift and amplitude attenuation between the induced and the sensed currents. Some of the induced current enters the strata through the drill bit and passes through the strata immediately below the drill bit, thereby providing an indication of that strata. The frequency of the currents induced by the first toroidal transformer may be varied to examine the strata

at different distances from the drill collar. High frequency signals are more highly attenuated by the strata then are low frequency signals, thus the penetration depth of the induced signals is inversely related to frequency. The data acquisition subsystem includes other sensors for measuring parameters such as weight and torque on the drill bit and pressures and also includes loggers for performing acoustic, radiographic, and directional logging.

Logging data thus acquired is communicated to the surface recording and control unit by the communication subsystem. A data transmitter modulates a carrier wave according to the data and drives the windings of a third toroidal transformer which in turn induces a current in the drill pipe that corresponds to the modulated wave. This current travels up the conductive drill pipe and is sensed at the surface by the surface recording and control unit. The down-hole communication subsystem also includes a receiver that is also coupled to the third toroidal transformer for receiving command signals from the surface unit.

The command and control subsystem of the down-hole measurement unit is responsive to the command signals received from the surface unit. These command signals direct the command and control subsystem to select the excitation frequency of the first toroidal transformer to obtain logging data for the surrounding strata at different distances from the drill bit. The command signals also select the data transmission frequency. The data transmission frequency is generally decreased to compensate for the additional signal attenuation caused by (1) increased drilling depth (space loss) or (2) decreases in the resistivity of

the earth strata being pentrated.

However, if the formation resistivity increases significantly at the drill bit, a different drill string excitation mode must be utilized in order to achieve optimum transmission up the drill string. In other words, if the earth in the vicinity of the lower part of the drill string below the transmitting toroid has such a large resistance that it no longer is effective as a ground plane (return circuit) it then becomes necessary to treat the drill string as a vertical dipole, immersed in a conductive media.

The best transfer of energy from the toroid to the drill string can be effected by finding the electrical resonance of the drill string in combination with the conducting media. The reasonance frequency can be determined at the down-hole module by sweeping the frequency applied to the transmitting toroid and determining the frequency at which maximum input current is drawn thereby. This frequency is then the optimum or tuned frequency. Alternatively, the optimum frequency can be selected at the surface unit by commanding the down-hole module to sweep the transmission frequency while monitoring the received signal level to detect the maximum signal amplitude. The down-hole module is then commanded to operate at this frequency. A discussion of technical theory relating to the above techniques can be found in an article by K.M. Lee and G.S. Smith, entitled "Measured Properties of Bare and Insulated Antennas in Sand," IEE Trans. Antennas and Propogat.., Vol. AP-23, pp. 664-670, September, 1975. At the lower frequencies, less data can be transmitted per unit time, so additional command signals direct the down-hole command and control subsystem to selectively transmit only the most

critical data.

Power for the circuitry of the down-hole measurement unit is provided by the power subsystem. The flow of drilling fluid down the hollow drill pipe rotates a turbine which in turn drives an alternator. The electrical output of the alternator is conditioned by a power supply and then is distributed to the various subsystemsin the down-hole measurement unit. Batteries provide back-up power for a limited time when the flow of drilling fluid is halted.

In a similar fashion, the surface recording and control unit is coupled to the drill pipe and includes the following: a communications subsystem, a data acquisition subsystem, and command and control subsystem, and a power subsystem. The communications subsystem has a data receiver for receiving logging data from the down-hole measurement unit and a command transmitter for transmitting command signals to the down-hole unit. A surface electrode is buried in the ground to provide a return path for the transmission signals.

The surface data acquisition subsystem consists of a microprocessor, interface circuitry, displays, and recorders. Functionally, it takes the logging data received by the communications subsystem, processes it, and outputs the corresponding information to various displays and recorders for communication to the operator.

The surface command and control subsystem controls the sequence of operations and makes decisions for the down-hole measurement unit as determined by internal programming or by operator initiated commands. This subsystem determines the command signals that direct the down-hole unit to vary its logging and

data transmission frequencies, as well as content of the transmitted data.

Power for the surface recording and control unit is independent of the drilling rig power and is provided by a motor generator set with a battery back-up.

An alternative embodiment of the present invention utilizes two toroidal transformers in the down-hole measurement unit. The previously described first toroidal transformer is eliminated, while the second toroidal transformer is retained. The previously described third toroidal transformer is additionally utilized for the purpose of inducing currents in the surrounding strata for logging. This toroidal transformer performs its three functions on a time-sharing basis: excitation transmission (for logging), data transmission, and command reception.

In another alternative embodiment the exictation signals for logging originate at the surface instead of down-hole.

Two additional alternative embodiments seek to reduce the attenuation of signals carried by the drill pipe. One embodiment utilizes passive couplers that inductively couple to the drill pipe and convey the signals in insulated wires to reduce transmission losses. Another embodiment used active relays to receive, boost, and re-transmit the signals.

An advantage of the present invention is that it provides the ability to characterize while drilling both adjacent and underlying strata at a range of distances from the drill bit.

Another advantage of the present invention is that it permits the variation of the frequency of data transmission to compensate for varying degrees of

transmission signal attenuation.

A further advantage of the present invention is that it provides two way communication between the down-hole measurement unit and the surface recording and control unit to allow interactive data logging.

Other objects and advantages of the present invention wll be apparent to those skilled in the art of well logging apparatus after having read the following detailed description of the preferred and alternative embodiments which are illustrated in the several figures of the attached drawing.

DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic and sectional view of a well drilling rig employing an information while drilling (IWD) system for use in logging data relating to well drilling.

Fig. 2 is a sectional view of a down-hole measurement unit utilized for down-hole information gathering in the information while drilling system of Fig. 1..

Fig. 3 is a sectional view of a toroidal transformer utilized as a transmitter in the down-hole measurement unit of Fig. 2.

Fig. 4 is a sectional view of a toroidal transformer utilized as a receiver for data logging in the down-hole measurement unit of Fig. 2.

Fig. 5 is a functional diagram of the information while drilling system of Fig. 1 including the down-hole measurement unit of Fig. 2 and a surface recording and control unit.

Fig. 6 is a functional diagram of the down-hole measurement unit of Fig. 2.

Fig. 7 is a functional diagram of the surface

recording and control unit utilized in the information while drilling system of Fig. 1.

Fig. 8 is a functional diagram of an alternative embodiment of an information while drilling system employing two toroidal transformers in a down-hole measurement unit for logging data and communicating with a surface recording and control unit.

Fig. 9 is a functional diagram of an alternative embodiment of an information while drilling system that used excitation signals generated by a surface excitation, recording, and control unit for logging data relating to well drilling.

Fig. 10 is a sectional view of an alternative embodiment of an information while drilling system which utilizes passive couplers for reducing the attenuation of transmission signals.

Fig. 11 is a sectional view of an alternative embodiment of a portion of an information while drilling system that employs active relays for improved communication between down-hole and surface units.

Fig. 12 is a functional diagram of an active relay utilized in the alternative embodiment of Fig. 11.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to Fig. 1, there is shown a cross-sectional view of a well 10, drilled by conventional rotary drilling apparatus, that employs a preferred embodiment of the present invention for logging information while drilling (IWD). Specifically, the conventional rotary drilling apparatus includes a drill pipe 12 (also known as a drill string) composed of a number of threadedly interconnected tubular pipe sections carrying at their lower end a modified drill

collar 13 terminated by a drill bit 14. At the surface 16, the drill pipe 12 is supported and rotated in direction 17 by standard apparatus (not shown) thereby rotating the drill bit 14 to advance the depth of the well 10.

A recirculating flow of drilling fluid 18 is utilzed to lubricate the drill bit 14 and to convey drill tailings and debris to the surface 16. Accordingly, the drilling fluid 18 is pumped down the well 10 by a pump 20 and flows through the interior of the drill pipe 12, as indicated by arrow 22, then through the drill bit 14 and up the annular cavity between the drill pipe 12 and the bore hole 24, as indicated by arrow 26.

Upon reaching the surface 16, the drilling fluid 18 is ducted by a pipe 28 to a settling pond 30 where the drill tailings precipitate from the drilling fluid. A portion of the drilling fluid 18 in the settling pond 30 spills over into a sump 32 where it is drawn into the pump 20 through an intake pipe 34 for recirculation through the well 10. Different types of drilling fluids are utilized depending upon the types of earth strata 36 encountered. Also forming part of the conventional rotary drilling apparatus is a casing pipe 38 that is inserted into the bore hole 24 from the surface 16 to prevent water and surrounding strata from entering the well 10.

Well logging while drilling is accomplished in an information while drilling (IWD) apparatus according to the present invention using a down-hole measurement unit or module 40 that is located in and forms a part of the drill collar 13 at the bottom of the drill string 12 just above the drill bit 14, and a surface recording and control unit 42 that is

coupled to the top of the drill pipe at the surface 16. Basically, the module 40 measures various parameters of the earth strata near the drill bit 14, along with various parameters dealing with the drilling operation, and conveys these measurements to the surface recording and control unit 42 via the drill collar 13 and the drill string 12. In order to function properly, the drill collar 13 and the drill string 12 must provide an electrically conductive path from the module 40 to the surface unit 42. Special care must be taken to ensure electrical continuity through each of the joints between sections of the drill string 12.

To assist in its measurement and communication tasks, the module 40 utilizes three toroidal transformers 44, 46, and 48 that are toroids consisting of magnetic material wound with insulated wire conductors. Each of the three toroidal transformers 44, 46 and 48 is positioned at spaced apart vertical locations coaxial with and encircling the drill collar 13 so that any current or signal flowing in the drill collar flows through the axial openings, or holes, of the toroids. The toroidal transformers can operate as either transmitters or receivers by inductively coupling current flow in the drill collar 13 into the coil conductors and vise versa. As a transmitter, a toroidal transformer induces a current flow in the encircled drill collar 13 in response to current flowing in its coil winding. Conversely, when acting as a receiver, a current flow is induced in the coil winding by the flow of current in the encircled drill collar 13.

The toroidal transformer 44, or excitation toroid, acts as a transmitter to induce an alternating

flow of current in the encircled drill collar 13. This induced current flows along the drill collar 13, the drill pipe string above, and the drill bit 14 below, and leaks into the surrounding strata 36 through contact at the drill bit below or through the drilling fluid 18 above. To form a complete circuit, current flows through the strata 36 near the well 10 as indicated by dashed lines 50 and 52.

The toroidal transformer 46, or logging toroid, is located just above the drill bit 14 and acts to sense the current flowing in the encircled drill collar 13 at that point. A portion of the induced current flowing in the drill collar 13 leaks into the strata 36 above the logging toroid 46 and flows therethrough as indicated by dashed lines 50. Meanwhile, the remainder of the induced current flows in the drill collar 13 through the axial opening of the logging toroid 46 and into the strata 36 along outer flow paths indicated by the lines 52. The portion of the induced current that leaks to the strata 36 below the logging toroid 46 versus the portion that leaks into the strata above the logging toroid is a function of the conductivity of the surrounding strata.

By using the logging toroid 46 as a receiver to sense the current flowing through the lower end of the drill collar 13, ie., through drill bit 14, and by knowing the current flow induced in the drill collar by the excitation toroid 44, the module 40 can characterize the surrounding strata 36. Additionally, by measuring the phase shift between the signal induced by the excitation toroid 44 and the signal sensed by the logging toroid 46, the dielectric constant of the surrounding strata 36 may be determined.

A large percentage of the current measured by the logging toroid 46 passes through the drill bit 14 and into the strata 54 below it. Placement of the logging toroid 46 as close to the drill bit 14 as is practical maximizes this percentage. Measuring the induced current that leaks into the strata 54 through the drill bit 14 thus characterizes the strata ahead of the drill bit.

Strata at a range of distances beneath the down-hole measurement unit 40 can be characterized by varying the frequency of the current induced by the excitation toroid 44. High frequency signals are attenuated more by the strata than are low frequency signals, thus, the penetration depth of the signals and the corresponding characterization depth is inversely related to frequency.

Data indicative of the surrounding strata as well as other data acquired by the module 40 must be communicated to the surface unit 42. To accomplish this, the third toroidal transformer 48, or transceiver toroid, is utilized as a transmitter to convey data to the surface 16 by inducing modulated alternating currents in the drill collar 13 and the drill string 12 for reception at the surface 16.

Command signals originating in the surface unit 42 must also be communicated to the down-hole module 40. Again, the drill pipe 12 is utilized as a conductor of a modulated alternating current for purposes of communication. In this case the toroid 48 acts to receive the command signals which, after passing through toroid 48, return through the strata as indicated by the dashed line 49.

The surface unit 42 may be coupled to the drill string 12 in several different ways. In one method,

a coupling 56 is provided for direct electrical connection between the drill string 12 and the surface unit 42. The function of the coupling 56 may be accomplished by any conductor in good electrical contact with the top of the drill string 12 and may be, for example, associated with a blow out preventer 60. In another method, a fourth toroidal transformer 58 is mounted to the bottom end of the casing pipe 38 prior to installation in the well 10 and is coupled to the surface unit 42 with a shielded cable 59. This toroid serves to inductively receive the signals transmitted up the drill string from the down-hole module 40 and to inductively transmit command signals from the surface unit 42 back into the drill string 12. The location indicated is particularly advantageous in eliminating atmospheric and surface generated noise thereby improving the signal-to-noise ratio of the transmitted signals.

A return path for the modulated alternating currents transmitted in the drill string 12 is provided by connection to an electrode 62 that is buried in the earth at 64. Current flows in the strata 36 between the electrode 62 and the drill bit 14 along a current flow path as indicated at 66. Leakage current flow paths as indicated at 68 also exist which attenuate the transmitted signals. Signal attenuation can be reduced by insulating the drill pipe 12 from the strata 36 by using an insulative drilling fluid 18 or an insulative coating on the external surface of the drill pipe. Signal attenuation can also be reduced by decreasing the transmitter frequency with a corresponding decrese in the rate of data transmission.

Details of the operation of the surface unit 42

as well as its interaction with the down-hole module 40 are described below.

In reference now to Fig. 2, the packaging and installation of the down-hole module 40 will now be described. A specially modified drill collar 13 provides a housing for the attachment of the various components of the module 40. The upper end of drill collar 13 is attached to the bottom section of the drill string 12 with a threaded connection 72. The lower end is provided with mounting threads 74 for the attachment of the drill bit 14.

To provide inductive coupling to the collar 13 for logging and communication, the three toroidal transformers 44, 46, and 48 are disposed at three, spaced-apart locations along the length of the cylindrical collar which forms an external housing for the module 40. The transceiver toroid 48 is located near the top of the collar 13, the logging toroid 46 is located directly above the drill bit 14, and the excitation toroid 44 is positioned between the transceiver and logging toroids. In each case, the toroids 44, 46, and 48 are recessed within annular grooves 43, 45 and 47 respectively, so that they encircle the collar 13. Consequently, currents flowing through the drill collar necessarily pass through the axial openings of the toroids.

Several sensors or transducers are attached to the drill collar 13 at various locations for measuring parameters such as temperatures, pressures, and forces that are of interest to the drilling rig operators. By way of example, two sensors 76 and 78 are shown disposed along the interior and exterior surfaces, respectively, of the collar 13 for monitoring the flow of drilling fluid 18. Forces such as weight and

torque on the drill bit 14 are monitored by a load transducer 80. All of the sensors and transducers 76, 78, and 80 along with all of the toroidal transformers 44, 46, and 48 are electrically coupled to an electronic system 82 via a wiring harness 84, Within the system 82 are electronic circuits that process data from the logging toroid 46 and from the sensors and transducers 76, 78, and 80, and communicate with the surface unit 42.

Electrical power is supplied to the system 82 by an alternator 86 coupled to a turbine 88 that is driven by the circulating drilling fluid 18. The alternator 86 is contained within a shell 90 that is attached to the collar 13 with resilient supports 92 and 94 which tend to isolate the shell somewhat from the vibrations of the drill collar. Upstream, the shaft 96 of the turbine 88 is rotatably coupled to a turbine support 98, while downstream, the shaft of the turbine is supported by the alternator 86 and its shell 90. Power from the alternator 86 is conveyed to the system 82 through a power cable 100.

In a fashion similar to that of the alternator 86, the electronic system 82 is housed within a shell 102 that provides a protective environment for the circuitry contained within. Resilient supports 104 and 106 position the shell 102 within the collar 13. Both of the shells 90 and 102 and all of the supports 92, 94, 98, 104, and 106 are preferably streamlined in shape so as to minimize their restriction to the flow of the drilling fluid 18.

Fig. 3 shows details of the configuration and operation of the excitation toroid 44. Physically, the excitation toroid 44 is composed of a toroidal shaped core 118 of a magnetic material such as iron

or ferrite with a coil winding 120 of insulated wire wrapped such that each loop of wire passes from the inside to the outside of the core. Two leads 122, and 124 of the coil winding 120 are connected to the system 82 through the wiring harness 84. The toroid is installed in the annular recess 43 formed in the collar 13 and is protected by an insulative cover 128 of potting material or the like.

In operation, an alternating current is caused to flow in the coil winding 120 as depicted at an instant of time by arrows 130. This current flow developes a magnetic field which in turn induces an electrical current 136 in the drill collar 13 causing electrical currents 138 to flow in the surrounding strata 36. These are used to accomplish logging of the strata.

The logging toroid 46 is constructed and mounted in a similar fashion and is schematically shown in Fig. 4 as it might appear prior to it mounting on the drill collar 13. As with toroid 44, insulated wire forming a coil winding 140 is wrapped around an annular core 142 of magnetic material and the leads 144 and 146 are coupled to the wiring harness 84 for connection to the system 82. The logging toroid 46 acts as a current detector and responds to a current flow, as indicated at 148, within the axial opening 149 of the toroid by establishing a magnetic field in the core 142. The direction of such field is depicted by arrow head 150 and arrow tail 152. This magnetic field induces an electrical current flow 154 in the coil winding 140 that is proportional to the current 148 passing through the axial opening 149 of the toroid. This induced current is subsequently utilized to characterize the surrounding strata 36. All three of

the down-hole toroidal transformers 44, 46, and 48 may be of substantially the same configuration in both construction and installation.

Well logging is accomplished in the information while drilling (IWD) apparatus, according to the preferred embodiment of the present invention, by using the drill string 12 as a means to effect communication between the down-hole module 40 and the surface unit 42.

The operation of the IWD system will now be generally described with reference to Fig. 5. . Also, the specific operation and configuration of the down-hole module 40 and the surface unit 42 will be described with reference to Figs. 6 and 7, respectively.

Both the down-hole module 40 and the surface unit 42 consist of four subsystems; namely, communications subsystems 156 and 158, command and control subsystems 160 and 162, data acquisition subsystems 164 and 166, and power subsystems 168 and 170 (down-hole module and surface unit respectively). Collectively, these subsystems perform the well logging and data communication functions of the IWD apparatus. In the down-hole module 40, all of the components of the subsystems are contained within the down-hole shell 102 with the exception of the toroidal transformers 44, 46, and 48, the sensors and transducers 76, 78, and 80, the turbine 88, and the alternator 86.

The data acquisition subsystem 164 provides for the measurement of certain parameters concerning the well drilling operation. Among the parameters of interest are the following: phase shift and attenuation of currents induced in the strata 36;

temperatures of the drill collar 13, drill bit 14, drilling fluid 18, and within shell 102; internal and external (annulus) pressures of the drilling fluid; weight and torque on the drill bit; drill bit wear; borehole deviation and direction; radiographic log of the strata using gamma rays and neutron bonbardment; and acoustic porosity log of the strata. Some of these parameters are measured or sensed within the shell 102, such as, for example, the radiograhic log and drilling direction, while other parameters are measured or sensed by sensors mounted on the drill collar 13, such as, for example, the excitation and logging toroids 44 and 46, the flow sensors 76 and 78, and the strain gages 80.

The down-hole data acquisition subsystem 164 includes a logging transmitter 172 for driving the excitation toroid 44, and a logging receiver 174 for processing signals from the logging toroid 46. Also included are external and internal sensors 176 and 178, and logging instrumentation 180 for gathering other desired data.

In the logging transmitter 172, the down-hole command and control subsystem 160 selects the frequency and power of the signal that drives the excitation toroid 44. A selectable frequency oscillator 182 and an excitation power control 184 are controlled by the down-hole command and control subsystem 160 for directing a power amplifier 186 in the generation of that signal. As an example, frequencies in the range between 1000 Hz to 30 MHz may be generated by the logging transmitter 172 for driving the excitation toroid 44 through its coil winding 130. The excitation toroid 44 is thus selectively operable to induce currents in the drill collar

13 over a wide range of frequencies.

A portion of the current induced in the drill collar 13 by the excitation toroid 44 is sensed by the logging toroid 46 and is characteristic of the conductivity and dielectric constant of the strata adjacent to the drill bit 14. Signals induced in the logging toroid 46 by the current flowing in the drill collar 13 are amplified and filtered by the logging receiver 174. Signals from the logging toroid 46 sequentially pass through a disconnect relay 188, a pre-amplifier 190, a selectable bandpass filter 192, and an automatic gain controlled amplifier 194 to provide a signal which is characteristic of the adjacent strata to the down-hole command and control subsystem 160.

The remainder of the down-hole data acquisition subsystem 164, namely the external and internal sensors 176 and 178, and the logging instrumentation 180, also gathers data concerning the drilling operation. External sensors 176 are positioned on the drill collar 13, and sense weight and torque on the drill bit 14, drilling fluid temperature, and drilling fluid pressure within the drill collar 13 and within the annular space between the drill collar 13 and the well bore 24.

The sensors and transducers 76, 78 and 80 shown in Fig. 2 are examples of external sensors 176. The internal sensors are contained within the preotective shell 102 and sense the temperature and pressure within the shell. Also contained within the protective shell 102 is the logging instrumentation 180 that logs radiographic and acoustic data concerning the strata adjacent to the drill collar 13. It also determines the direction in which the drill bit 14 is

drilling. Data gathered by the external and internal sensors 176 and 178, as well as data gathered by the logging instrumentation, is input to the down-hole command and control subsystem 160 for further processing and transmission to the surface unit 42.

The heart of the down-hole measurement unit is the down-hole command and control subsystem 160. It acts to collect data from the data acquisition subsystem 164, processes and analyses the data, determines priorities for data communication either internally or upon command from the surface unit 42, controls the output of the excitation toroid 44, distributes power from the down-hole power subsystem 168 to various circuitry within the module 40, and controls communications by determining transmission frequency and power, and reception frequency.

This is accomplished by providing a microprocessor 196 with a programmable read only memory (PROM) 198, a random access memory (RAM) 200, and an electrically eraseable programmable read only memory (EEPROM) 202 interconnected in a well known manner. The computer thus formed is interfaced to the remainder of the down-hole module through an input/output digital converter 206. Two analog multiplexers 208 and 210 are provided to selectively switch data inputs to the computer. Data from the external and internal sensors 176 and 178 are boosted by a conditioning amplifier 212, while data from the logging receiver 174 is transformed from alternating to direct current signals by a rectifier 214. Operating instructions may be stored in the PROM 198 and the EEPROM 202, or may be down-loaded from the surface unit 42 and stored in the RAM 200.

Power for the operation of the down-hole module

40 is provided by the turbine driven alternator 86, with a battery powered back-up 216. Selection between the two sources of power is accomplished by a power switch 218 that is controlled by the down-hole command and control subsystem 160 in response to an input power sensor 220. When the flow of drilling fluid 18 slows significantly, or stops, the power switch 218 switches in the back-up power unit 216 to allow the down-hole module to continue to function. Since the power generated by the alternator can vary widely in voltage and frequency, it is regulated, rectified and filtered by a power supply 222 which supplies clean power to the down-hole command and control subsystem 160 for distribution throughout the down-hole unit 40.

The down-hole module 40 and the surface unit 42 are linked together through bi-directional communications. Each unit includes a communications subsystem which permits the transmission of command signals from the surface unit 42 to the down-hole module 40, and the transmission of measurement data from the down-hole module to the surface unit. The communication signals are preferably carrier waves modulated by phase-shift or frequency modulation. These communication signals are carried by the conductive drill string 12 between the down-hole module 40 and and surface unit 42. Transmission frequency is varied as a function of the signal attenuation present in the transmission line (drill pipe 12 and collar 13). Signal attenuation increases as the well deepens, so the transmission frequency is decreased to compensate. The frequency band used may, for example, be between 20 Hz and 1000 Hz.

Operationally, the down-hole communications

subsystem 156 receives command signals from the surface unit 42 and transmits measurement data signals to the surface unit. Connection to the drill collar 13 is provided by inductive coupling through the transceiver toroid 48. The coil windings of the transceiver toroid 48 are connected to a diplexer 222 which functions as a switch to alternately connect the transceiver toroid to either a command receiver 224 or a data transmitter 226. Both the command receiver 224 and the data transmitter 226 are coupled to the down-hole command and control subsystem 160 for transmission frequency selection and data transfer.

Specifically, the command receiver contains a pre-amplifier 228, two automatic gain controlled amplifiers 230 and 232, two selectable bandpass filters 234 and 236, a limiter 238, and a demodulator 240. Functionally, command signals induced in the coil windings of the transceiver toroid 48 are directed by the diplexer 222 to the pre-amplifier 228 for amplification. From there, the command signals pass through the first automatic gain controlled amplifier 230 and the first selectable bandpass filter 234 for filtering in a frequency range determined by the down-hole command and control subsystem 160. Next, the command signals pass through the second automatic gain controlled amplifier 232 and the second selectable bandpass filter 236 and into the limiter 238. Finally, the command signals are demodulated by the demodulator 240 and sent to the down-hole command and control subsystem 160 for further action.

Data signals, containing the logging data obtained by the down-hole data acquisition subsystem 164, are input to the data transmitter 226 by the

down-hole command and control subsystem 160 for transmission to the surface unit 42. To do so, the data signals are input to a modulator 242 for conversion to a modulated waveform which is then input to a selectable frequency oscillator 244 that sets the frequency of the carrier wave as directed by the down-hole command and control subsystem 160. Continuing, the signal enters a power amplifier 246 for boosting, then passes through the diplexer 222 and to the coil windings of the transceiver toroid 48 for inductive coupling into the drill collar 13. The power level of the boosted signal is monitored by an output power sensor 248 and is controlled by an output power controller 250, both coupled to the down-hole command and control subsystem 160.

Functionally, the surface communications subsystem 158 is very similar to the down-hole communications subsystem. It contains a data receiver 252 for receiving measurement data signals from the down-hole measurement unit 40 and a command transmitter 254 for transmitting command signals to the down-hole unit. A diplexer 256 alternately couples either the data receiver 252 or the command transmitter 254 to the top of the drill pipe 12 and to the electrode 62 for directly accessing the electrical currents flowing in the drill pipe. In an alternative embodiment, the diplexer connects the drill string 12 to the electrode 62 and alternately couples either the data receiver 252 or the command transmitter 254 to the fourth toroidal transformer 58 for indirectly accessing the electrical currents flowing in the drill string.

Signals entering the data receiver 252 first pass through a passive bandpass filter 258 then through an amplification and filtering circuit that

is identical in form and function to that of the command receiver 224. Specifically, this circuit includes a pre-amplifier 260, two automatic gain controlled amplifiers 262 and 264, two selectable band-pass filters 266 and 268, a limiter 270 and a demodulator 272. The filters are coupled to the surface command and control subsystem 162 for frequency selection. The output of the demodulator, which contains the measurement data from the down-hole measurement unit 40, is coupled to the surface data acquisition subsystem 166 for further processing.

In a corresponding fashion, the command transmitter 254 is identical in form and function to the data transmitter 226 of the down-hole communications subsystem 156. A modulator 274, a selectable frequency oscillator 276, a power amplifier 278, an output power sensor 280, and an output power control 282, all function as do their down-hole counterparts. Accordingly, command signals from the surface command and control subsystem 162 are processed to yield a modulated signal of selected frequency and power for transmission in the drill string 12.

Electrical power for the surface unit 42 is provided by the surface power subsystem 170. A motor generator 284 provides the primary source of power while a battery source or the drilling rig motor generator provides a power back-up 286. Selection between the two sources of power is accomplished by a power switch 288 that is controlled by the surface command and control subsystem 162 in response to an input power sensor 290. Power conditioning including voltage regulation and noise filtering is necessary and is provided by a power supply 292. The conditioned power is routed within the surface unit 42 by

the surface command and control subsystem 162.

Data acquisition and command and control is accomplished in the surface recording and control unit 42 by a surface controller 294 in conjunction with several input and output devices 296 and 298. The data acquisition functions consist of processing measurement data from the data receiver 252 and converting it to a format suitable for output. Concurrently, the command and control functions include generating command signals for transmission to the down-hole measurement unit 40 for controlling logging frequency and data transmission frequency and content. The command and control functions also include interfacing to the various surface subsystems for communication with the outside world and for power distribution.

These functions are provided in the surface controller 294 by a computer 300 that includes a microprocessor 302, a programmable read only memory (PROM) 304, a random access memory (RAM) 306, and an electrically eraseable programmable read only memory (EEPROM) 308, all interconnected in a manner well known in the art. Interfacing to the computer 300 and the remainder of the surface unit 42 is provided by an input/output buffer 310. Signals from the output power sensor 280 and the input power sensor 290 are connected to the I/O buffer 310 through an analog multiplexer 312, a rectifier 314 and an analog to digital converter 316. Operating instructions for the surface controller may be stored in the PROM 304 or the EEPROM 308 or it may be input by the operator or down-loaded from a storage device.

System input and output is provided at two locations, namely a logging operator station 318 and

a drill rig station 320. Control panels 322 and 324, data/status displays 326 and 328, chart recorders 330 and 332, and warning indicators 334 and 336 are located at both stations 318 and 320. Additionally, the drill rig station 320 includes a depth measure device 338 for inputing the well depth, and the logging operator station 318 includes a printer 340 and data and program storage devices 342.

As described above, the IWD apparatus measures and records well drilling data on a real-time basis.

An alternative embodiment of the present invention, shown in Fig. 8, includes a down-hole module 348 that combines the functions of the excitation and transceiver toroids 44 and 46 by employing a transceiver and excitation toroid 350 for both communications and logging excitation. In this embodiment, a data and logging transmitter 352 is operable for the generation of both data communication signals and logging signals of relatively low frequency. These signals may be, for example, in the 20 Hz to 1000 Hz range.

Since the data and logging transmitter 352 serves both communications and data acquisition functions, it and all other communications and data acquisition related components may be combined into a communications and data acquisition subsystem 354. This subsystem 354 functions in a manner identical to the communications subsystem 156 and the data acquisition subsystem 164 of the previously described embodiment with one exception. The transceiver and excitation toroid 350 connects on a time-sharing basis to the command receiver 224 and the data and logging transmitter 352. Thus, the data transmission, command reception, and logging excitation functions occur sequentially, not simultaneously. The remainder

of the down-hole measurement unit 348 functions as previously described.

In another alternative embodiment of the present invention, shown in Fig. 9, a surface recording and control unit 356 contains a logging transmitter 358 for generating logging signals at the surface for transmission down-hole to a down-hole module 360. Accordingly, a switch 362 sequentially connects the data receiver 252, the command transmitter 254, and the logging transmitter 358 to the drill pipe 12 and electrode 62 for reception of data or transmission of commands or logging signals. Frequency and power of the logging signals is determined by a surface controller 364 according to stored operating instructions or operator input. The combination of the logging transmitter 358 and the surface controller 364, along with the input and output devices 296 and 298, form a surface command, control, and data acquisition subsystem 366. Apart from the addition of the logging transmitter 358, the surface command, control, and data acquisition subsystem 366 is identical to the combination of the previously described surface command and control subsystem 162 and surface data acquisition subsystem 166.

In this embodiment, logging signals transmitted down the drill pipe 12, are sensed by the logging toroid 46 as previously described. Due to the long transmission path, the logging signals are transmitted at a relatively low frequency to limit signal attenuation. Consequently, a logging receiver 368 is provided in a down-hole data acquisition subsystem 370 for amplifying and filtering the low frequency signals sensed by the logging toroid 46. Apart from the removal of the logging transmitter 172 and excitation

toroid 44, the present down-hole measurement unit 360 is equivalent in form and function to the previously described down-hole measurement unit 40.

Referring now to Fig. 10, an additional feature of the present invention is shown which includes passive couplers 376 used to reduce the attenuation of signals transmitted through the drill string 12. Reduction of signal attenuation is desireable in order to utilize transmission signals of high frequency for maximizing data transfer rates. By reducing signal attenuation, the passive couplers permit higher frequency transmissions of measurement data and command signals between the surface unit 42 and the down-hole module 40 than would otherwise be possible.

Each passive coupler consists of a down-hole contact 378, a couping toroid 380, and an insulated cable 382 interconnecting the two. Mounting for the coupling toroid 380 is provided by an annular coupling body 384 which is inserted into and forms a part of the drill string 12 and is disposed perhaps 1000 or more feet above the down-hole module 40. Attachment of the coupling unit to the drill string 12 is provided by threaded connections 72 that are normally used for attachment of drill pipe sections. The conductor of the insulated cable 382 is attached through a connector 385 to one lead of the toroid coil windings while the other lead is grounded to the coupling body. Suspended from the unit 384 by the insulated cable 382, the down-hole contact 378 establishes electrical contact with the inside of the drill collar 13 below the transceiver toroid 48. A weight 386 is attached to the down-hole contact 378 to insure a taut insulated cable 382 and, thus, a correctly positioned down-hole contact.

In operation, during data transmissions, the transceiver toroid 48 induces a current indicated by arrow 388 in the insulated (not shielded) cable 382 as well as in the drill collar 13. This current (arrow 388) travels up the insulated cable 382, and through the coil windings of the coupling toroid 380. A return path for a return current (arrow 390) is provided by the drill pipe 12 and drill collar 13 to the contact point of the down-hole contact 378. The flow of current in the coil windings of the coupling toroid 380 acts to induce a corresponding current in the coupling body 384 and the drill string 12. It may also induce current in cable 392 of another passive coupler 394. In this way, passive couplers 376 may be stacked to convey signals along the drill pipe 12 in stages. Signal attenuation is thus reduced through the use of insulated cables. This method of reducing signal attenuation is also bi-directional since the passive couplers 376 are mutually coupled.

The utiliztion of passive couplers 376 is straight forward and can easily be implemented. For example, as drilling progresses, a depth will be reached where drill string signal attenuation becomes a problem. At that point, the coupling unit 384 may be attached to the top of the drill string 12 and the down-hole contact lowered into position and connected at the connector 385. Drilling then continues until another passive coupler 394 is needed. One key advantage to this method is its passive operation, ie., no additional power is required. The insulated cable can also be made up in pre-determined lengths for ease of handling.

Another additional feature of the present invention includes the provision of an active repeater

396 which is utilized to overcome the effects of signal attenuation (see Figs. 11 and 12). In this embodiment, a relay toroid 398 is mounted on a coupling unit 399 in a fashion similar to the transceiver toroid 48. A relay shell 401 is suspended within the coupling sub 399 in a fashion similar to the module shell 102 described earlier. Positioned within the relay shell, a relay electronics unit 400 is provided containing a diplexer 402, a relay receiver 404, a relay controller 406, a relay transmitter 408, and a power supply 410. Electrical connection between the windings of the relay toroid 398 and the relay electroncis unit 400 is provided by a cable 412.

In operation, the relay toroid 398 inductively senses signals conveyed through the drill string 12. The relay receiver 404 is connected to the relay toroid 398 through the diplexer 402 and amplifies and filters the inductively sensed signals for input to the relay controller 406. These signals are delayed and stored by the relay controller 406 for a period of time, then output to the replay transmitter 408 for retransmission up the drill string by the relay toroid 398. Power for the relay circuitry is provided by either batteries or a turbine/alternator combination as in the down-hole module 40.

As will be clear to those skilled in the art, modifications and changes may be made to the disclosed embodiments without departing from the inventive concepts thereof. The above description is intended as illustrative and informative but not limiting in scope. Accordingly, it is intended that the following claims be interpreted to cover all modifications that reasonably fall within the scope of the invention.

What is claimed is:

CLAIMS

1. Information while drilling apparatus for detecting and communicating via a conductive drill string data including information relative to down-hole parameters and characteristics of the earth strata in the vicinity of the drill bit, comprising:

excitation source means for establishing excitation currents which pass through the earth strata, the drill bit, and the electrically conductive drill string;

down-hole module means including

an elongated, electrically conductive, cylindrical housing forming a drill collar means for connecting said drill bit to the lower end of said drill string,

first toroidal transformer means disposed at the lower end of said module for detecting excitation currents flowing through said drill bit and for developing corresponding logging currents,

first current detecting means responsive to said logging currents and operative to develop corresponding first data signals, and

first signal coupling means for coupling said first data signals into said drill string; and

communication means coupled to said drill string for receiving said logging signals.

2. Information while drilling apparatus as recited in claim 1 wherein said excitation source means is located at the surface of said well and includes

current generating means for generating said excitation currents,

electrode means buried in the earth's surface at a location distant from the well and coupled to said generating means for introducing said excitation currents into said earth strata; and

means coupling the upper end of said drill string to said generating means to provide a return path for said excitation currents.

3. Information while drilling apparatus as recited in claim 2 wherein said current generating means are selectively caused to develop excitation currents variable over a range of frequencies and amplitudes.

4. Information while drilling apparatus as recited in claim 1 wherein said first transformer means encircles the lower end portion of said housing such that excitation currents flowing along the length of said housing induce corresponding logging currents in the windings of said transformer means.

5. Information while drilling apparatus as recited in claims 1, 3 or 4, wherein said first detecting means includes

first receiver means coupled to the output of said first transformer means for processing said logging currents,

first transmitting means coupled to the output of said first receiver means and operative to generate said first data signals, and

wherein said module means further includes power supply means for providing electrical power to said

first detecting means.

6. Information while drilling apparatus as recited in claim 5 said first signal coupling means includes second toroidal transformer means which is disposed to encircle said housing at a position spaced from said first transformer means and serves to electromagnetically couple data signals between said first transmitting means and said drill string.

7. Information while drilling apparatus as recited in claim 6 wherein said module means further includes

sensor means for monitoring at least one downhole parameter other than current sensed by said first current detecting means and for developing corresponding second data signals for input to said first transmitting means.

8. Information while drilling as recited in claim 7 wherein said excitation source means also generates control signal currents which pass through said earth strata, the portion of said housing encircled by said second transformer means, and said drill string, said second transformer means developing control signals in response to the passage of said control signal currents passing therethrough, and

wherein said module means further includes module control means responsive to said control signals and operative to control the transmission of said first data signals and said second data signals via said first transmitting means.

9. Information while drilling apparatus as recited in claim 8 wherein said module control means

also controls the frequency of the data transmissions effected by said first transmitting means.

10. Information while drilling apparatus as recited in claim 6 wherein said module means further includes

third toroidal transformer means disposed to encircle said housing at another position spaced from said first transformer means, and

second transmitting means for causing said third transformer means to develop localized logging currents in the strata surrounding the lower end of said drill string, said localized currents also flowing through said drill bit and said housing.

11. Information while drilling apparatus as recited in claim 10 wherein said second transmitting means includes signal source means for generating logging signals having frequencies selectable over a predetermined range, said signals causing said localized logging currents to have a particular selected frequency characteristic.

12. Information while drilling apparatus as recited in claim 11 wherein the selection of the frequency of the logging signals generated by said second transmitting means is controlled by said module control means.

13. Information while drilling apparatus as recited in claim 1 wherein said module means further includes

sensor means for monitoring various down-hole conditions and parameters and for developing corres-

ponding signals for input to said first transmitting means.

14. Information while drilling apparatus as recited in claim 13 wherein said excitation source means also generates control signal currents which pass through said earth strata, the portion of said housing encircled by said second transformer means, and said drill string, said second transformer means developing control signals in response to the passage of said control signal currents passing therethrough, and

wherein said module means further includes module control means responsive to said control signals and operative to control the transmission of said first data signals and said second data signals via said data transmitting means.

15. Information while drilling apparatus as recited in claim 14 wherein said module control means also controls the frequency of the data transmissions effected by said data transmitting means.

16. Informaion while drilling apparatus as recited in claim 15 wherein said module control means determines the resonant frequency of the drill string and causes said data transmitting means to transmit at such reasonant frequency.

17. Information while drilling apparatus as recited in claim 15 wherein said communication means determines the optimum transmission frequency and causes said excitation source means to generate control signals which are received by said module control means

which in turn causes said data transmitting means to transmit at said optimum frequency.

18. Information while drilling apparatus as recited in claim 17 wherein said optimum frequency is the resonant frequency of said drill string and is sensed by sweeping said transmission frequency and determining the frequency at which the amplitude of the signals received by said communication means is maximum.

19. Information while drilling apparatus as recited in claim 5 wherein said power supply means includes

turbine means positioned within said housing and driven by drilling fluid flowing through said drill string,

power generating means driven by said turbine for generating electrical power while said drilling fluid is flowing,

battery means for supplying electrical power when said drilling fluid is not flowing,

means for regulating and filtering electrical power from said power generating means and said battery means so that it is suitable for use by the varous electrical circuits contained within said downhole module means, and

switching means responsive to the flow of drilling fluid through said drill string and operative to selective either said power generating means or said battery means as the source of power for said module means.

20. Information while drilling apparatus as

recited in claim 9 wherein said power supply means includes

turbine means positioned within said housing and driven by drilling fluid flowing through said drill string,

power generating means driven by said turbine for generating electrical power while said drilling fluid is flowing,

battery means for supplying electrical power when said drilling fluid is not flowing,

means for regulating and filtering electrical power from said power generating means and said battery means so that it is suitable for use by the various electrical circuits contained within said downhole module means, and

switching means responsive to the flow of drilling fluid through said drill string and operative to select either said power generating means or said battery as the source of power for said module means.

21. Information while drilling apparatus as recited in claim 15 wherein said first detecting means includes

first receiver means coupled to the output of said first transformer means for processing said logging currents,

first transmitting means coupled to the output of said first receiver means and operative to generate said first data signals, and

wherein said first signal coupling means includes

second toroidal transformer means disposed to encircle said housing at a position spaced from said first transformer means and serving to electromagneti-

cally couple data signals between said first transmitting means and said drill string.

22. Information while drilling apparatus as recited in claim 21 wherein said module means further includes

third toroidal transformer means which is disposed to encircle said housing at another position spaced from said first transformer means, and

second transmitting means for causing said third transformer means to develop localized logging currents in the strata surrounding the lower end of said drill string, said localized currents also flowing through said drill bit and said housing.

23. Information while drilling apparatus as recited in claim 22 wherein said second transmitting means inclues signal source means for generating logging signals having frequencies selectable over a predetermined range, said signals causing said localized logging currents to have a particular selected frequency characteristic.

24. Information while drilling apparatus as recited in claim 1, 3, 4, 15, or 23, and further comprising:

remote coupler means including

an electrically conductive cylindrical coupler housing forming a part of said conductive drill string;

a remote coupler toroidal transformer means encircling said coupler housing and having one lead of its toroidal winding electrically connected to said coupler housing;

an insulated conductor of predetermined length having one end electrically connected to said coupler housing and its other end electrically connected to said wiper contactor, said conductor being disposed to extend down the inside of said drill string with said wiper contactor electrically contacting said drill string at a point below said first signal coupling means whereby said first signal coupling means induces said first data signals in said conductor and said conductor communicates said logging signals to said remote transformer means which in turn couples said logging signals back into said drill string.

25. Information while drilling apparatus as recited in claim 24 and further comprising additional remote coupler means sequentialy positioned along said drill string with the wiper contactor of each remote coupler means being disposed bewlow the transformer means of the next lower remote coupler means.

26. Information while drilling apparatus as recited in claims 1, 3, 4, 15 or 23, and further comprising relay means disposed along the length of said drill string and operative to extract a communicative data signal induced on said drill string at a lower level and to re-introduce said communicative data signal onto said drill string.

27. Information while drilling apparatus as recited in claim 26 wherein said relay means includes a toroidal relay transformer means for use in re-introducing said communicative data signals onto said drill string.

28. Information while drilling apparatus as recited in claim 27 wherein said relay means further includes active signal processing means for detecting data signals induced in said relay transformer means, processing the detected data signals and then inducing corresponding data signals onto said drill string via said relay transformer means.

29. Information while drilling apparatus as recited in claim 28 wherein said signal processing means includes storage means for temporarily storing said detected data signals.

30. Information while drilling apparatus as recited in claims 29 wherein said data signals are shifted in frequency prior to re-introduction onto said drill string.

31. In a telemetry system utilizing a first toroidal transformer means to induce comunicative currents into a electrically conductive drill string, and one or more relay means disposed along said drill string for relaying the communicative information upward, an improved relay means comprising:

an electrically conductive cylindrical member disposed along and forming a part of said drill string;

second toroidal transformer means encircling said cylindrical member and having one lead of its toroidal winding electrically connected to said drill string;

an insulated conductor of predetermined length extending down the internal passageway of said drill string and having one end connected to the other lead of said toroidal winding and its other end affixed to

a contactor means disposed beneath said first toroidal transformer means whereby said first transformer means induces communicated currents in said conductor and such currents flow through the windings of said second transformer means which in turn induce a corresponding communicative current flow in said drill string.

32. Information while drilling apparatus for detecting and communicating data including information relating to down-hole conditions and characteristics of the earth strata in the vicinity of the drill bit, comprising:

down-hole module means having an elongated electrically conductive, cylindrical housing for coupling a drill bit to the lower end of an electrically conductive drill string, said module means including

first excitation source means disposed along the length of said housing for establishing excitation currents which flow through said drill bit, said housing and the earth strata surrounding said drill bit;

first toroidal transformer means disposed proximate the lower end of said housing for detecting excitation currents flowing through said drill bit and for developing corresponding logging currents in the output windings thereof,

detecting means responsive to said logging currents and operative to develop corresponding logging signals, and

signal coupling means disposed along the the length of said housing for coupling said logging signals into said drill string for communication to the surface; and

surface communication means coupled to said drill string for receiving said logging signals.

33. Information while logging apparatus as recited in claim 32 wherein said excitation source means includes an excitation signal generating means and a second toroidal transformer means coupled thereto for developing said excitation currents.

34. Information while drilling apparatus as recited in claim 33 wherein said second transformer means encircles said housing at a point spaced apart from said first transformer means.

35. Information while drilling apparatus as recited in claim 34 wherein said excitation signal generating means is capable of causing said excitation transformer means to develop excitation currents which are selectively variable over a range of frequencies.

36. Information while drilling apparatus as recited in claim 35 wherein said detecting means include receiver means for filtering and amplifying said logging currents, and

transmitter means for converting the output of said receiver means into logging signals of a form suitable for transmission along said drill string.

37. Information while drilling apparatus as recited in claim 36 wherein said signal coupling means includes a third toroidal transformer means disposed to encircle said housing at a point proximate the upper end thereof.

38. Information while drilling apparatus as recited in claim 37 wherein said surface communication means is inductively coupled to said drill string through a fourth toroidal transformer means encircling said drill string.

39. Information while drilling apparatus as recited in claim 38 wherein said fourth toroidal transformer means is positioned at a sub-surface location and is coupled to said communication means by a shielded cable.

40. Information while drilling apparatus as recited in claims 32 or 39 wherein said module means further includes,

turbine means positioned within said housing and driven by the flow of drilling fluid passing through said drill string, and

power generating means driven by said turbine means for supplying electrical power for said module means while drilling fluid is flowing through said drill string.

41. Information while drilling apparatus as recited in claim 40 wherein said module means further includes battery means for supplying electrical power for said module means when said drilling fluid is not flowing, and

switching means sensitive to the flow of drilling fluid and operable to connect either said power generating means or said battery means to the electrical components contained within said housing depending on whether or not said drilling fluid is flowing.

42. Information while drilling apparatus as recited in claim 41 and further comprising:

control means for establishing control currents which flow from said surface through said earth strata, said module housing and said drill string; and

wherein said module means further includes control means for detecting said control currents and controlling the operation of said module means inaccordance therewith.

43. Information while drilling apparatus as recited in claim 42 wherein said signal coupling means couples said control currents into said control means.

44. Information while drilling apparatus as recited in claim 43 wherein said module means further includes sensor means for monitoring various down-hole conditions and parameters, said sensor means being coupled to said transmitter means whereby signals developed by said sensor means is transmitted along said drill string.

45. A method for logging a well while drilling by detecting characteristics of the earth strata adjacent to a drill bit affixed to the lower end of an electrically conductive drill string, said method comprising the steps of:

disposing a first toroidal transformer around the drill string immediately above said drill bit;

using a current source displaced from said frist toroidal transformer to cause a flow of current through the lower portion of the drill string, the drill bit and the earth strata proximate thereto; and

sensing the flow of current through said drill bit by measuring the current induced in said first toroidal transformer by said flow of current.

46. A method for logging a well while drilling as recited in claim 45 wherein said flow of current is caused by energizing a second toroidal transformer disposed about said drill string in spaced apart relationship to said first toroidal transformer.

47. A method for logging a well while drilling as recited in claim 46 wherein certain characteristics of said strata in the vicinity of said drill bit are determined by energizing said second transformer with alternating currents and comparing the phase of the energizing signal to the phase of the signal induced in said first transformer.

48. A method for logging a well while drilling as recited in claims 45, 46 or 47, wherein information is obtained from the current induced in said first transformer by converting it into a suitable data form and transmitting the data to the surface via the conductive drill string.

49. A method for logging a well while drilling as recited in claum 48 wherein the characteristics of the earth strata lying beneath the drill bit are determined by changing the frequency of the signal used to energize said second transformer.

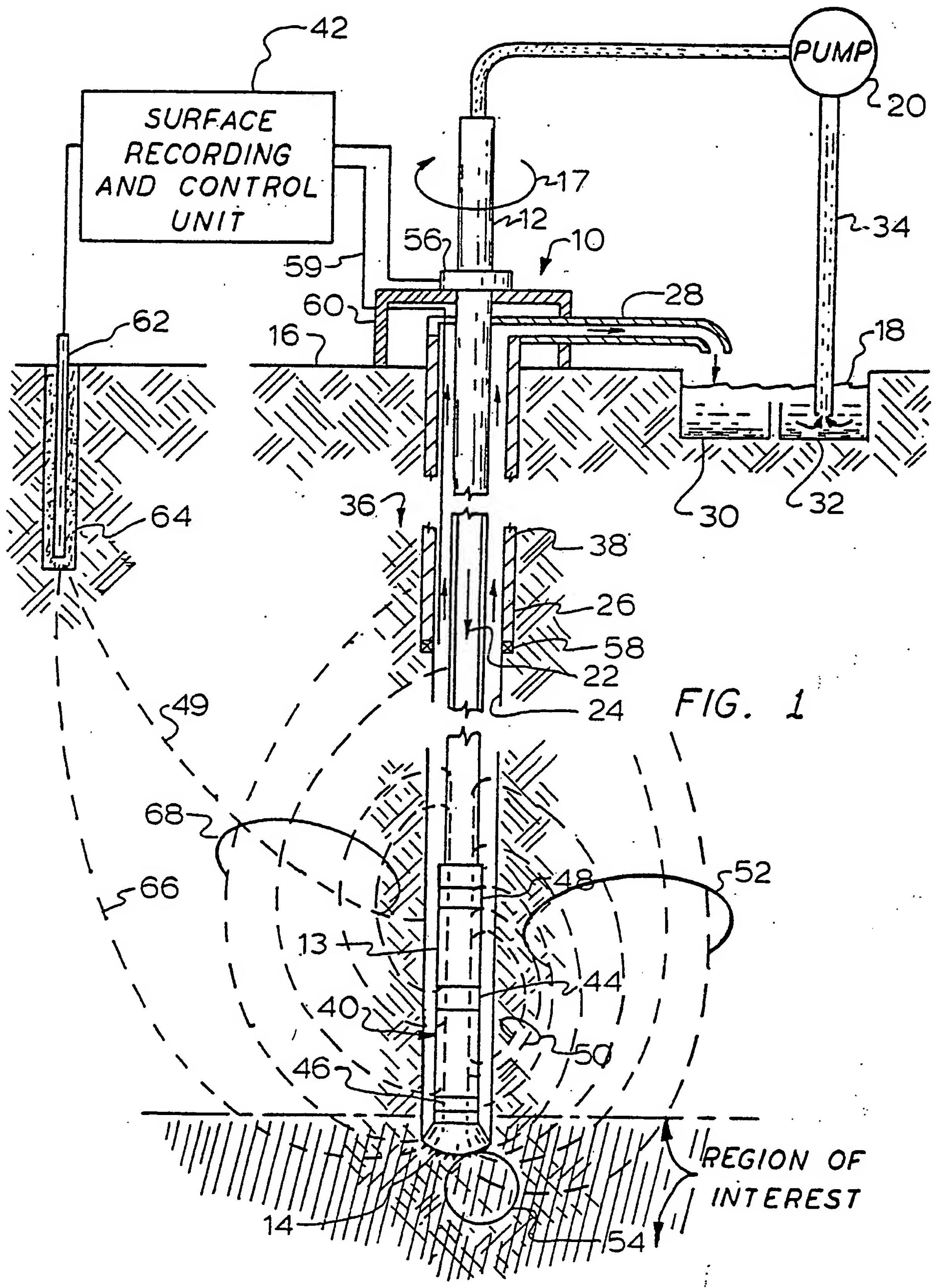
50. A method for logging a well while drilling as recited in claim 48 wherein said suitable data form is obtained by modulating a transmission frequency

with the data to be transmitted, and whether said method further comprises:

varying the transmission frequency over a range of frequencies;

determining the particular frequency at which maximum transmission current is conducted through said drill string; and

using said particular frequency to transmit said data.


42
SURFACE RECORDING AND CONTROL UNIT
PUMP
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REGION OF INTEREST
14
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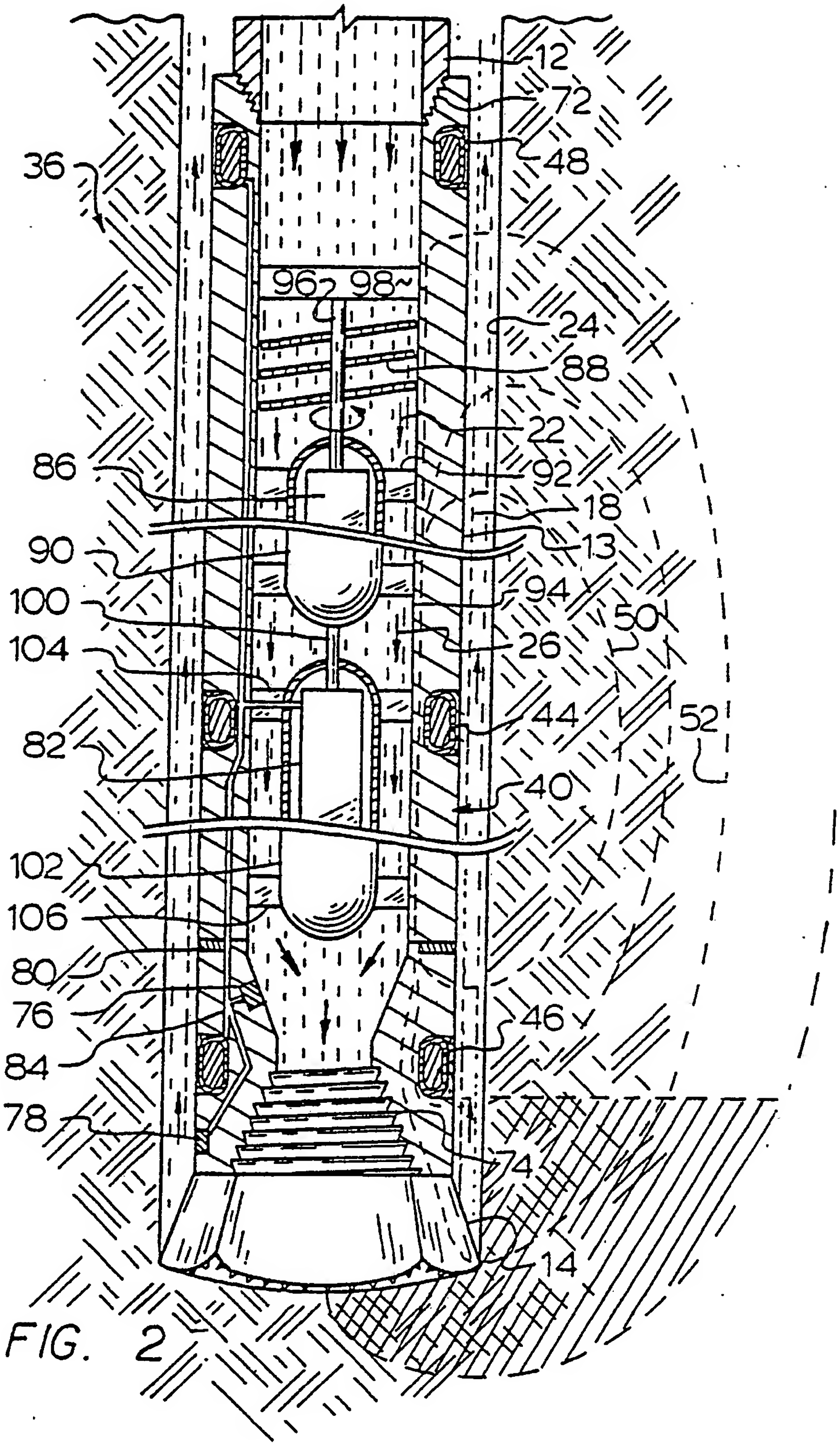
FIG. 1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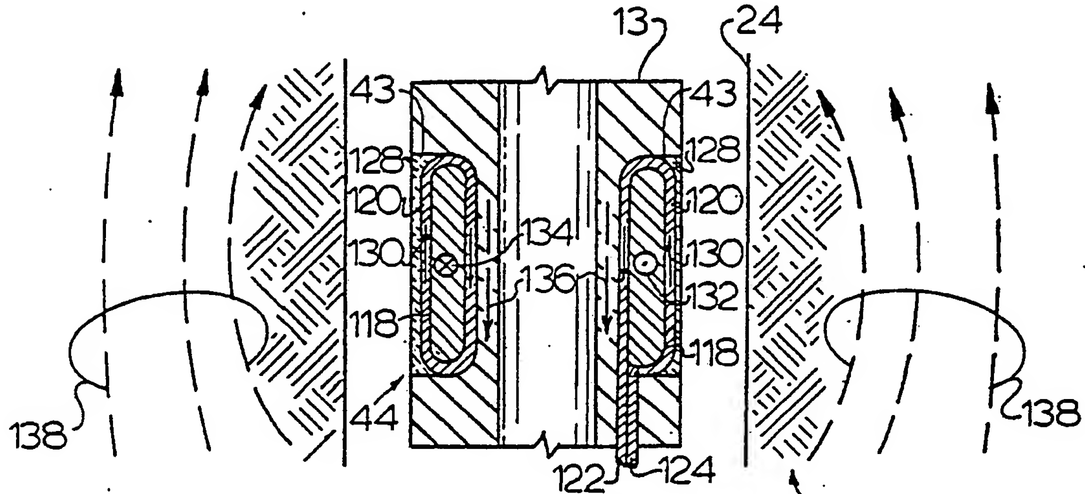
82
40
102
106
80
76
46
84
78
74
14

FIG. 2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24
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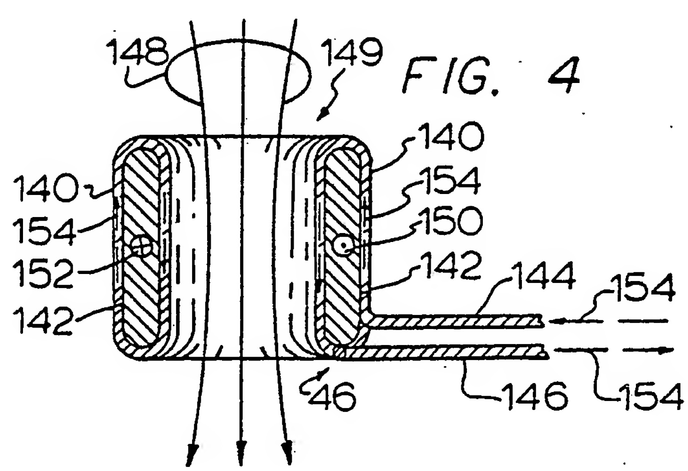
36

FIG. 3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154
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150
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142
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144
154
146
154
46

FIG. 4

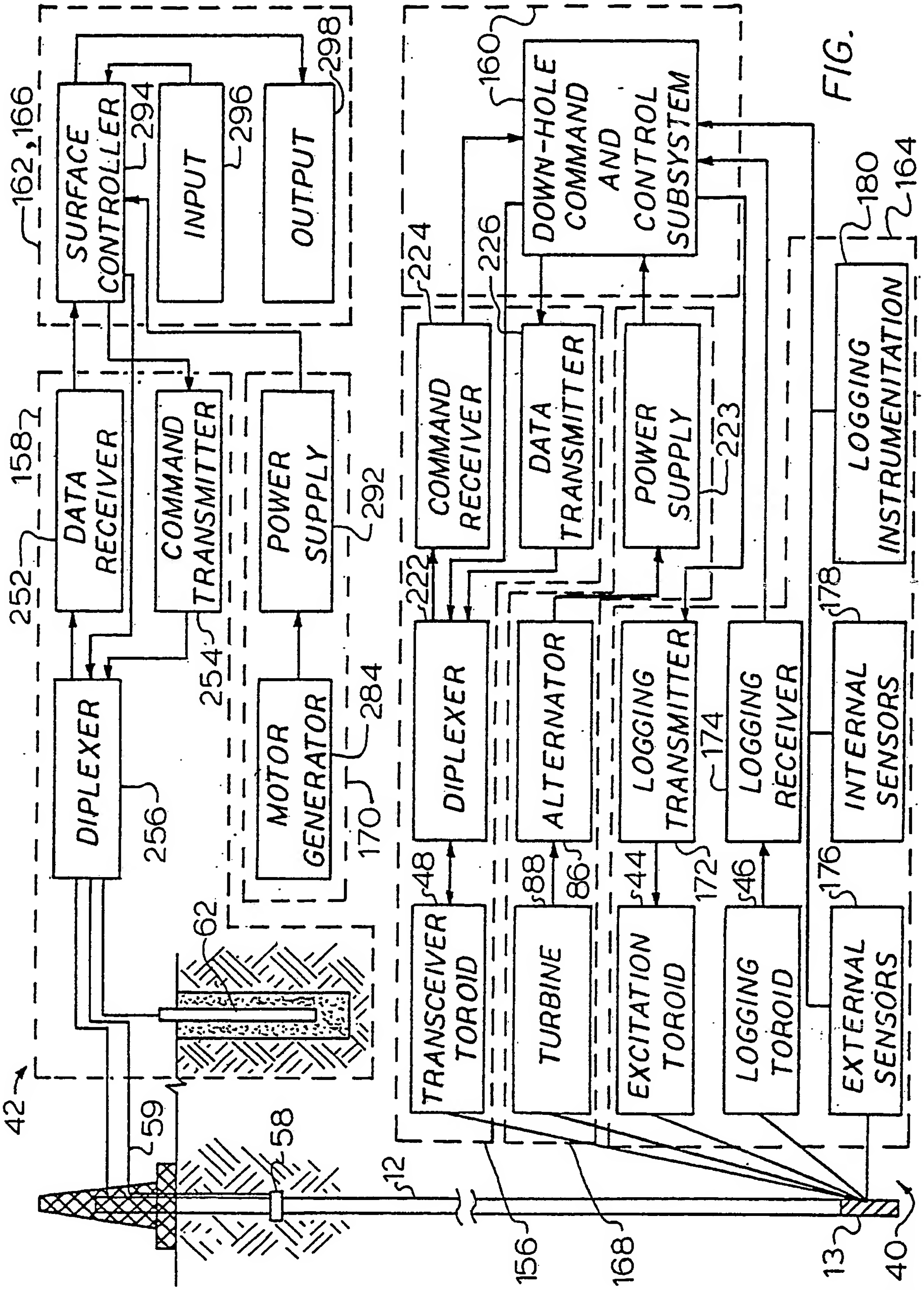

SURFACE CONTROLLER
INPUT
OUTPUT
162,166
294
296
298
DATA RECEIVER
COMMAND TRANSMITTER
POWER SUPPLY
158
252
254
292
DIPLEXER
256
MOTOR GENERATOR
284
170
62
42
59
58
12
DOWN-HOLE COMMAND AND CONTROL SUBSYSTEM
160
COMMAND RECEIVER
DATA TRANSMITTER
POWER SUPPLY
224
226
223
222
DIPLEXER
ALTERNATOR
LOGGING TRANSMITTER
LOGGING RECEIVER
INTERNAL SENSORS
LOGGING INSTRUMENTATION
180
164
178
174
172
TRANSCEIVER TOROID
TURBINE
EXCITATION TOROID
LOGGING TOROID
EXTERNAL SENSORS
48
88
86
44
46
176
156
168
13
40

FIG. 5

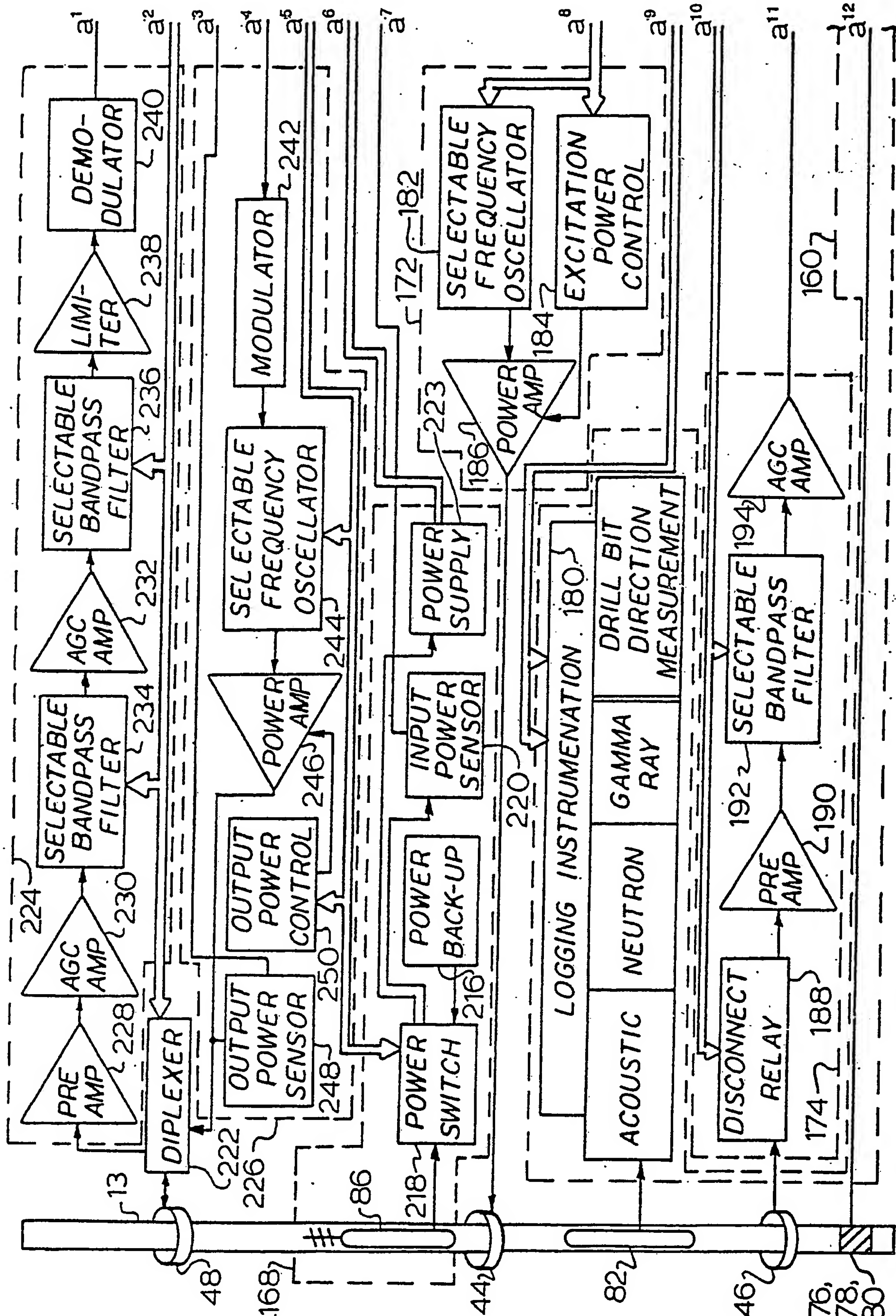


FIG. 6a

SUBSTITUTE SHEET

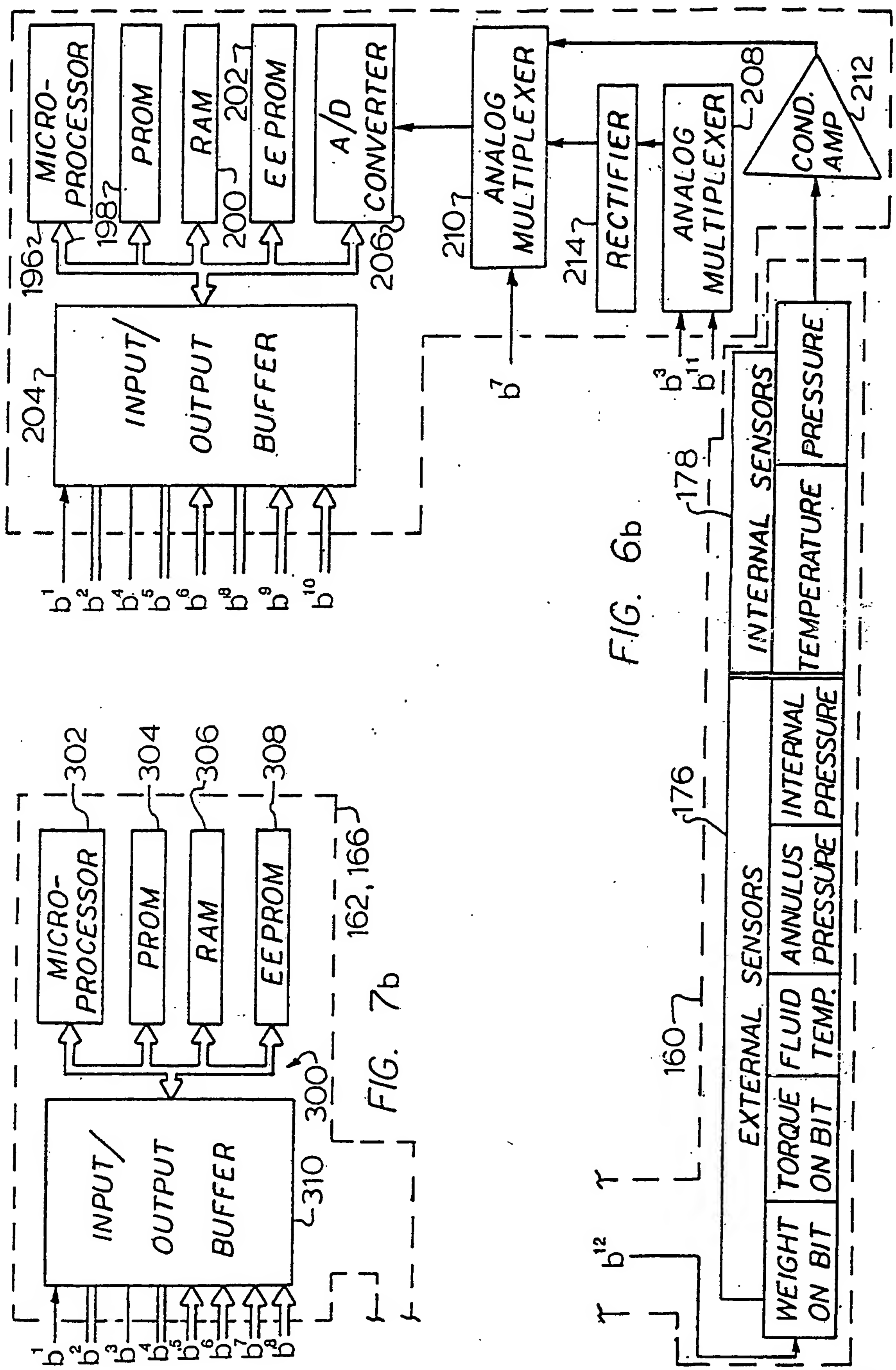

MICRO-PROCESSOR
PROM
RAM
EE PROM
A/D CONVERTER
ANALOG MULTIPLEXER
RECTIFIER
ANALOG MULTIPLEXER
COND. AMP
INPUT/ OUTPUT BUFFER
INTERNAL SENSORS
TEMPERATURE
PRESSURE
EXTERNAL SENSORS
WEIGHT ON BIT
TORQUE ON BIT
FLUID TEMP.
ANNULUS PRESSURE
INTERNAL PRESSURE
196
198
200
202
204
206
208
210
212
214
178
176
160
MICRO-PROCESSOR
PROM
RAM
EEPROM
INPUT/ OUTPUT BUFFER
300
302
304
306
308
310
162, 166

FIG. 6b

FIG. 7b

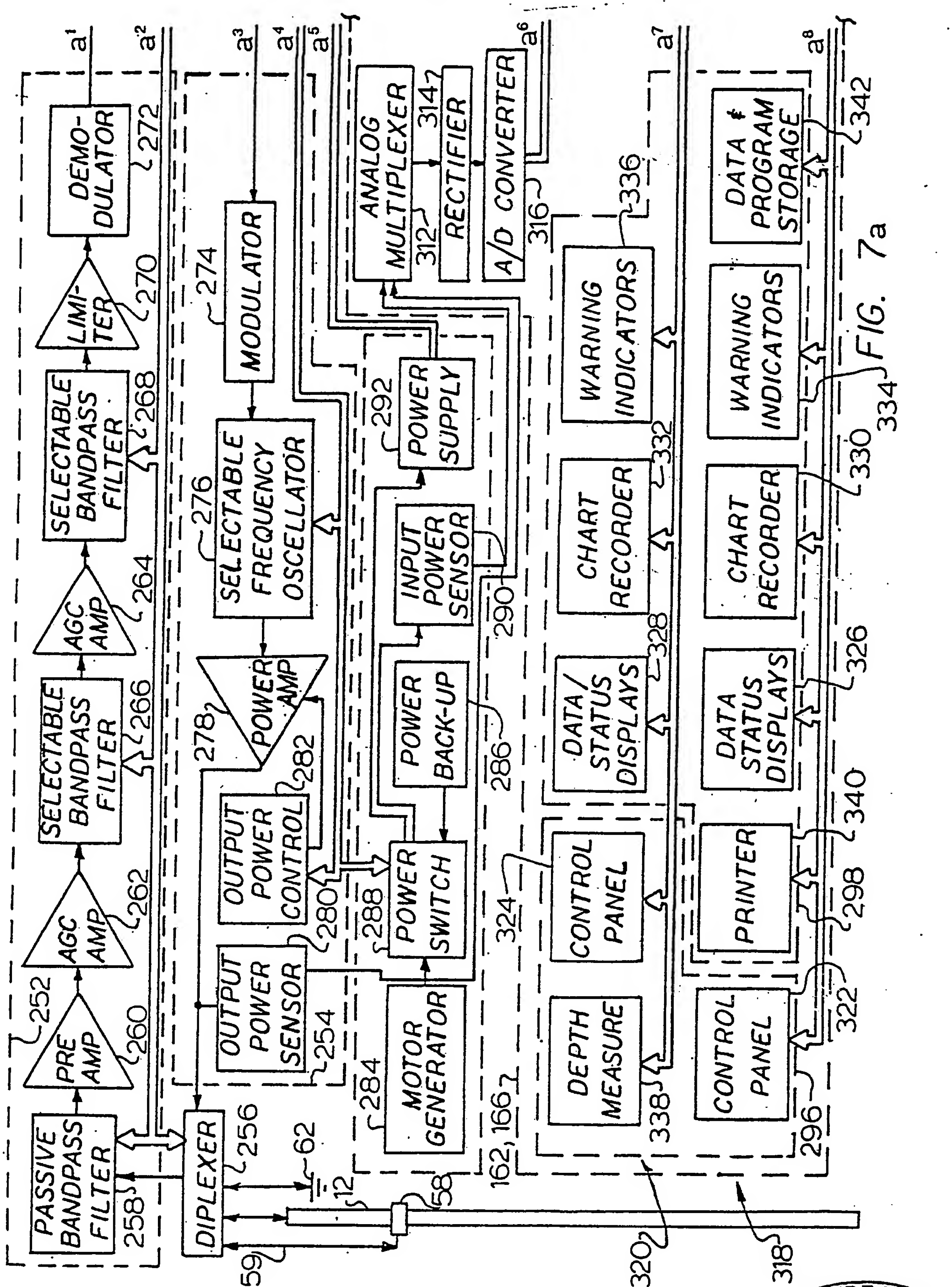
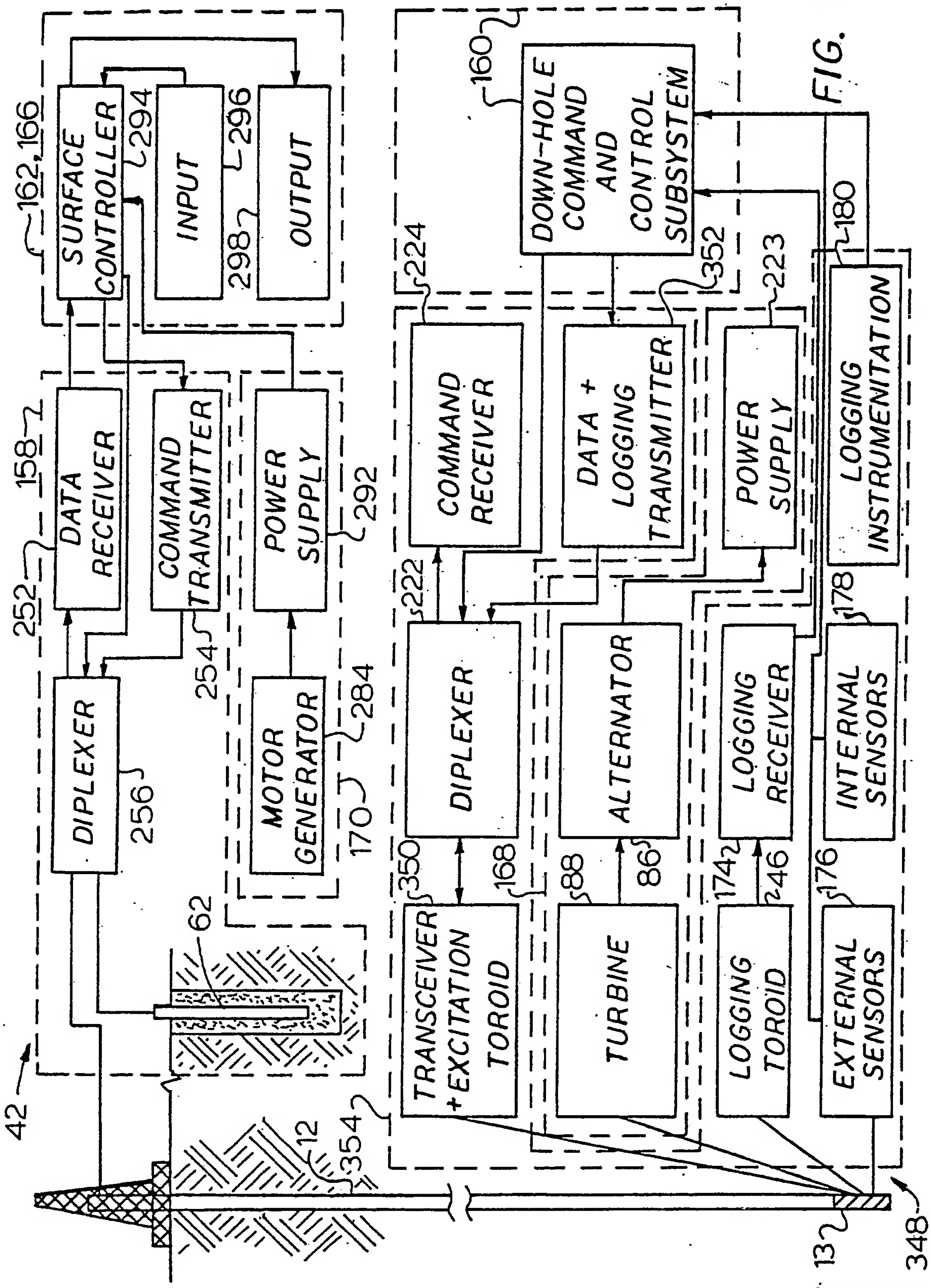


FIG. 7a

SUBSTITUTE SHEET


SURFACE CONTROLLER
INPUT
OUTPUT
DATA RECEIVER
COMMAND TRANSMITTER
POWER SUPPLY
DIPLEXER
MOTOR GENERATOR
DOWN-HOLE COMMAND AND CONTROL SUBSYSTEM
COMMAND RECEIVER
DATA + LOGGING TRANSMITTER
POWER SUPPLY
LOGGING INSTRUMENITATION
DIPLEXER
ALTERNATOR
LOGGING RECEIVER
INTERNAL SENSORS
TRANSCEIVER +EXCITATION TOROID
TURBINE
LOGGING TOROID
EXTERNAL SENSORS
162,166
294
296
298
158
252
254
256
292
284
170
62
42
12
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13
348
160
224
352
223
180
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350
88
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174
246
176
178

FIG. 8

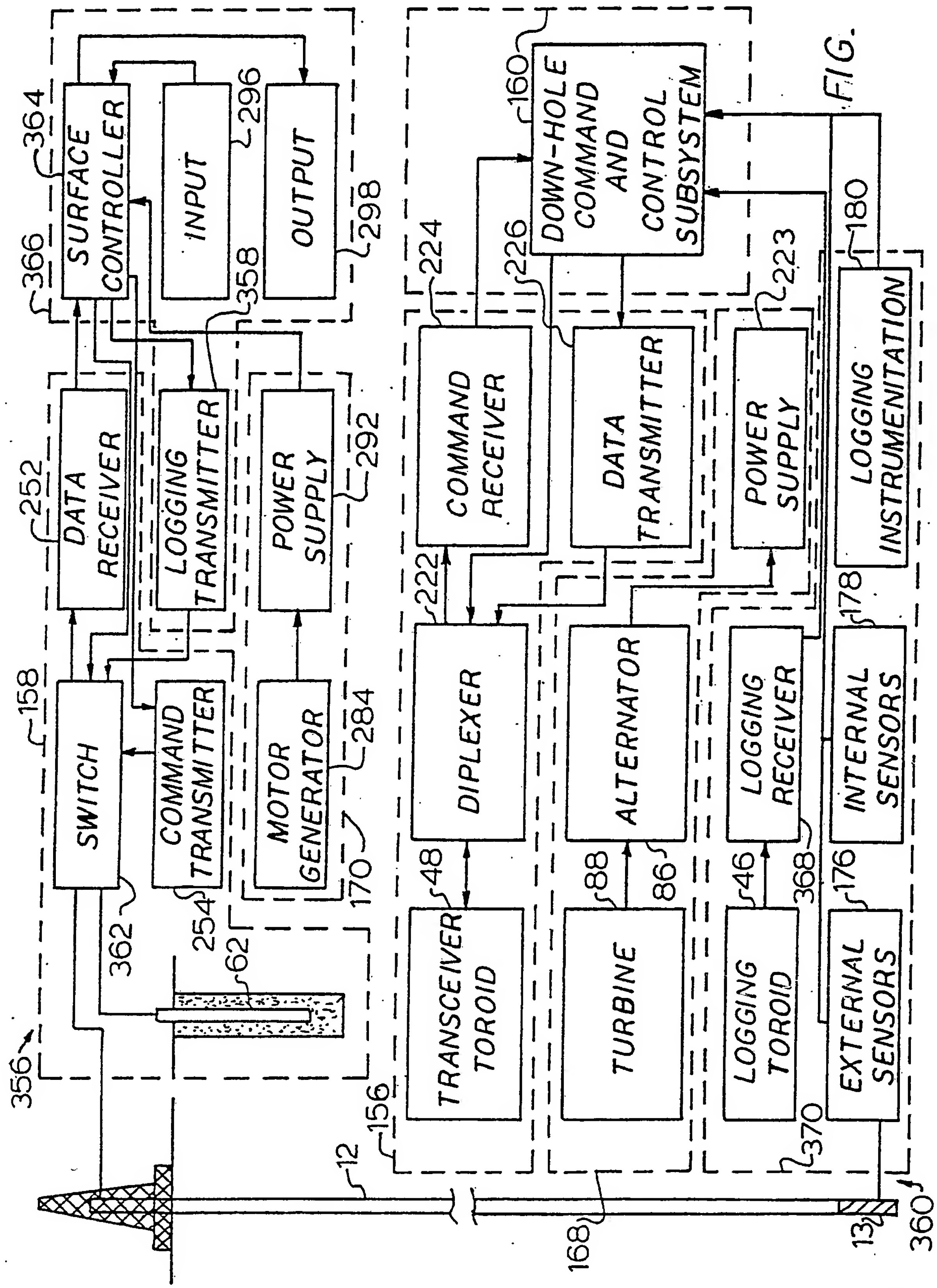

SURFACE CONTROLLER
INPUT
OUTPUT
DATA RECEIVER
LOGGING TRANSMITTER
POWER SUPPLY
SWITCH
COMMAND TRANSMITTER
MOTOR GENERATOR
DOWN-HOLE COMMAND AND CONTROL SUBSYSTEM
COMMAND RECEIVER
DATA TRANSMITTER
POWER SUPPLY
LOGGING INSTRUMENITATION
DIPLEXER
ALTERNATOR
LOGGING RECEIVER
INTERNAL SENSORS
TRANSCEIVER TOROID
TURBINE
LOGGING TOROID
EXTERNAL SENSORS
364
366
296
298
358
252
292
158
284
170
254
362
62
356
160
224
226
223
180
222
178
48
88
86
46
368
176
156
12
370
168
13
360

FIG. 9

FIG. 12

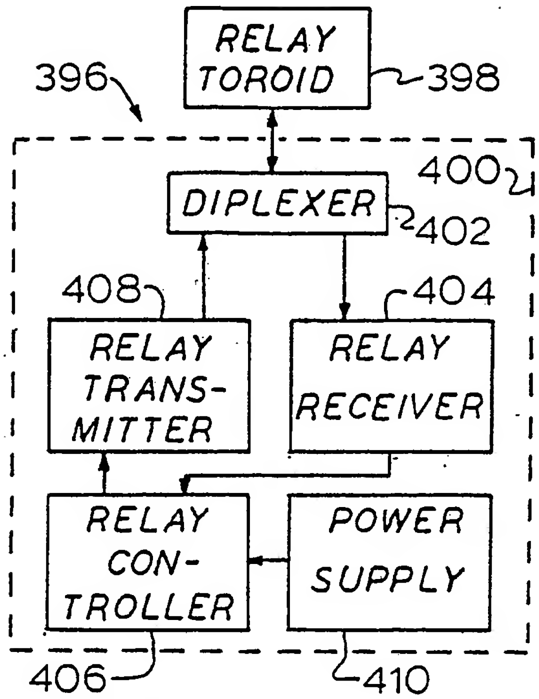
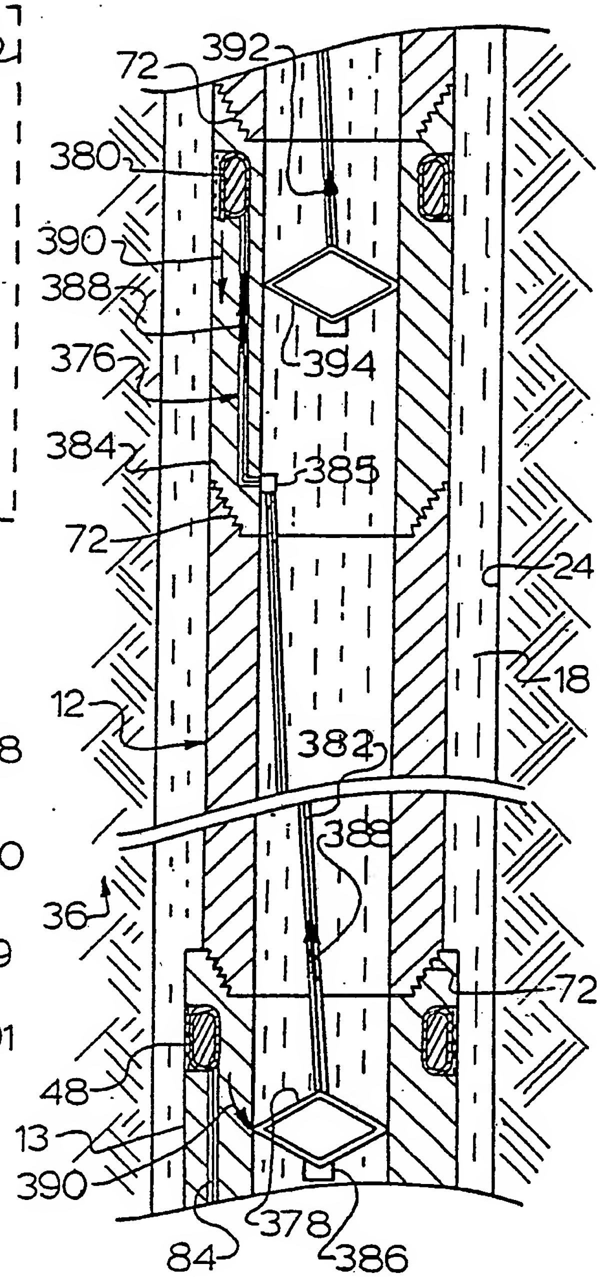


FIG. 10



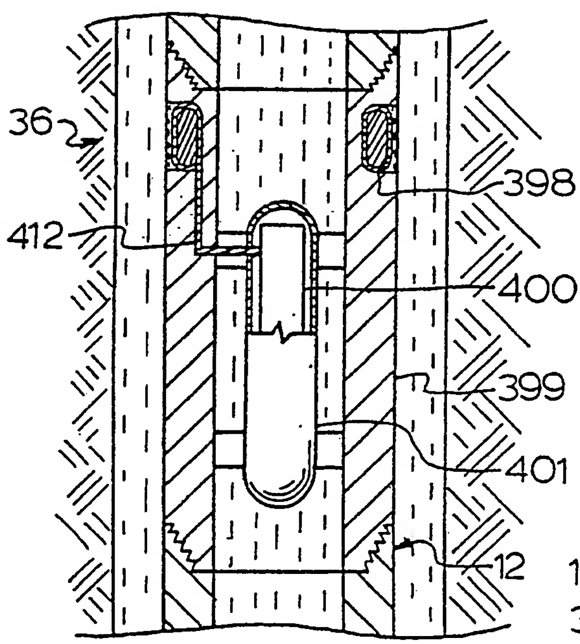


FIG. 11

INTERNATIONAL SEARCH REPORT

International Application No PCT/US83/01548

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [3]

According to International Patent Classification (IPC) or to both National Classification and IPC
Int. Cl. 3 G01V 1/40; E21B 47/00
U.S. Cl. 340/854, 856; 166/65R; 324/356,369

II. FIELDS SEARCHED

Minimum Documentation Searched [4]

Classification System	Classification Symbols
U.S.	340/854,856; 166/65R; 175/40,50; 324/356,369

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [5]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [14]

Category *	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No. [18]
X	US, A, 2,411,696 (Silverman et al) 26 November 1946	1,45,48/45
X	UK, A, 2,076,039 (Russell) 25 November 1981	1,2,5/1,32, 33
Y	US, A, 4,348,672 (Givler) 7 Septembet 1982	1-50
A	US, A, 4,181,014 (Zuvela et al) 1 January 1980	1-50
A	US, A, 3,090,031 (Lord) 14 May 1963	1-50

* Special categories of cited documents: [15]
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search [2]	Date of Mailing of this International Search Report [2]
12/1/84	18 JAN 1984
International Searching Authority [1]	**Signature of Authorized Officer [20]**
ISA/US	N. Moskowitz